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BIOLOGICAL EFFECTS OF BLAST FROM BOMBS. GLASS FRAGMENTS AS PENETRATING MISSILES AND SOME OF THE BIOLOGICAL IMPLICATIONS OF GLASS FRAGMENTED BY ATOMIC EXPLOSIONS

Progress Report

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BIOLOGICAL EFFECTS OF BLAST FROM BOMBS

Glass Fragments as Penetrating Missiles and Some of the Biological Implications of Glass Fragmented by Atomic Explosions

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ABSTRACT

An exploratory study was made whose aim was to evaluate the damage done by low velocity (less than 1000 ft/sec) missiles consisting of small fragments of ordinary window glass striking in random orientations a biological target. The index of damage was chosen to be the penetration of the abdominal wall of anesthetized dogs. By use of appropriate laboratory data, a criterion of penetration was derived which expresses in equation form the probability of penetration in terms of missile mass and impact velocity.

The penetration criterion was applied individually to data for 2486 glass missiles originating in test houses placed on Operation Teapot (5) at various ranges from ground zero.

By use of other statistical procedures, expectation of penetration was computed as a function of overpressure for the region between 1.9 and 5.0 psi. It was found that maximum expectation occurred at about 3.8 psi.

The general biological significance of the results obtained was discussed.

ACKNOWLEDGMENTS

CHAPTER 1

INTRODUCTION

There is ample evidence that debris set in motion by an explosion is a major cause of injury (1, 2, 3, 4). This fact prompted a field study of missiles produced by atomic detonation during the Nevada Test Series held in the spring of 1955. Among other things, the results, which have been reported elsewhere (5), dealt with fragments of window glass shattered by the blast. Using appropriate methods, over 2400 glass missiles were collected in a manner which allowed determination of the mass and the impact velocity of each fragment.

Following the field work, it seemed desirable to initiate exploratory experiments in the laboratory which would aid in assessing the biological meaning of the physical data obtained in Nevada. Accordingly, a biophysical study was undertaken employing the abdomen of an anesthetized experimental animal as a target for glass fragments of various masses and impact velocities. Conditions critical for penetration of the abdominal wall were determined in terms of the mass and the velocity of the missile, and the data were analyzed statistically in order to define the probability of penetration as a function of these two parameters.

The purposes of this report are first, to present the results of the biophysical study mentioned above, and second, to describe the application of such information to selected portions of the field missile data in order to determine, so far as is possible, the biological implications of the latter.

CHAPTER 2

METHODS

2.1 General

The general methods employed in the laboratory study have been described in detail elsewhere (5). Briefly, the missiles, consisting of glass fragments mounted in a Styrofoam sabot, were fired from an air gun at the abdominal wall of anesthetized dogs. In each experiment the missile velocity over the last foot of travel in the gun barrel was measured with a Hewlett-Packard Chronometer triggered photoelectrically. This muzzle velocity was corrected to impact velocity using data obtained previously (5) with a high speed Fastax Camera. Past experience has indicated that the velocity measurements were accurate within ±1 per cent.

2.2 Missiles

Missiles were obtained by shattering ordinary window glass into small fragments with a hammer. The thickness of the panes of glass ranged from 0.1 to 0.2 in. After weighing, the fragments were segregated into 5 weight groups, the mean masses of which were 0.0543, 0.131, 0.318, 0.769 and 1.895 gms. The variation about the mean weight in each group did not exceed 5 per cent. The missiles employed were selected from these groups, care being exercised to randomize missile shape.

2.3 Velocity

In each of the 5 groups of experiments involving missiles of different masses, from 2 to 4 series of experiments were accomplished employing a fairly constant impact velocity in each series, though the velocity was varied from series to series. The missile velocities were selected to produce high,

low and intermediate percentages of penetration of the abdominal wall in each group. Eventually 16 series of experiments were accomplished at the average velocities noted in Table 2.1. The table shows the general plan utilized to accumulate data in an orderly manner. Enough usable shots were fired, 389 in all, to establish a statistically reliable relationship between per cent penetration and missile mass and velocity.

2.4 Target

Fourteen pure bred Dalmatian dogs, ranging between 6.5 and 7 months in age and coming from 2 litters, were used in the experiments. All but 4 were males. The weights ranged from 26 to 40 lbs, averaging 33 lbs. Each animal was deeply anesthetized with intraperitoneal Nembutal (60 mg/lb) and the fur was shaved from the abdominal wall. Missiles were aimed in such a way as to strike the target in rows allowing about 0.75 to 1.0 in. between missiles. Approximately 2 to 4 rows of 10 shots each were accomplished with each animal. Immediately after each shot the abdominal wall was inspected and "wounds of entry", if any, were recorded. Probing the skin lacerations did not serve as a very reliable means of determining penetration of the abdominal wall. However, location of "wounds of exit" proved satisfactory and this was easily accomplished, after sacrifice of the animal by exsanguination, by turning back flaps of the abdominal wall and recording the perforations of the peritoneum easily visible as small round regions of hemorrhage.

2.5 Analytical Procedures

The penetration data obtained in the several series of experiments were analyzed by standard statistical practice (7, 8). The details of each analysis are given in Chapter 4.

CHAPTER 3

RESULTS

3.1 Penetration Figures

The results of the laboratory penetration study are shown in Table 3.1. The original data have been grouped to show the number of missile shots accomplished for each velocity series (Column E), the average missile velocities along with the standard deviations in velocity (Column C), the ranges in impact velocities in each series (Column D), the per cent of missiles which penetrated the skin based on "wounds of entry" (Column F) and the per cent of fragments which penetrated into the abdominal cavity based on "wounds of exit" (Column G). Column H indicates for 3 series, the average velocity of those glass fragments which penetrated the abdominal wall.

It is apparent from Columns B, C, F and G of Table 3.1 that penetration of the skin and abdominal wall by glass missiles was a function of both missile mass and impact velocity, that on the whole the heavier missiles penetrated at lower impact velocities, and that for a given missile weight, the higher the velocity the greater the likelihood of penetration.

3.2 Gross Pathology

Examination of the abdominal wall and viscera were accomplished after sacrifice of each experimental animal. As could be expected massive hemoperitoneum was noted upon opening the abdominal cavity. Multiple perforations of the large bowel and several loops of the small intestines were sometimes present. Among the several dogs, intra-abdominal glass fragments were found lodged in the small intestines, buried in the liver, spleen, kidneys and stomach,

and others were found lying free in the peritoneal cavity. In no instance did a missile pass entirely through an animal, though in a few cases fragments had pierced the peritoneal cavity and organs and were arrested by the body wall opposite the initial wound.

In addition to inspection of the target area of the abdominal wall to determine the number of penetrations of the skin and peritoneum already referred to and noted in Table 3.1, other findings were of interest. In those several instances in which the missiles struck the skin and bounced away 3 observations were made; namely, sometimes no mark was apparent, often only a raised welt was noted and fairly frequently small skin lacerations were seen. Penetration of the skin was a frequent finding and often rather copious hemorrhage occurred from these wounds during the shooting period prior to sacrifice of the animal. In many cases, fragments passing through the skin did not enter the abdomen and these usually were found lodged in the muscular tissue of the abdominal wall.

In no case was there definite evidence that a glass missile broke after impact with the skin. For instance, no broken missiles were found in the muscles of the abdominal wall even though many of the glass fragments failed to pierce the peritoneum. Also relevant was the observation that the peritoneal "wounds of exit" from the target area were regular and spaced in rows as were the "wounds of entry" through the skin. In case the missiles broke, irregularity in alignment of the peritoneal wounds would have been expected and, of course, if missile fragmentation were a prominent affair, more "wounds of exit" than "wounds of entry" could have occurred. Consequently, though fragmentation — particularly of the larger glass missiles — might have happened occasionally, it no doubt was an infrequent event indeed.

CHAPTER 4

ANALYSIS OF LABORATORY DATA

4.1 General Approach

The penetration data presented in Table 3.1 were used to deduce the general empirical relationship between the probability of penetration and missile mass and velocity. The operations used in the analysis are outlined below:

a. Using the data shown in Table 3.1, the relationship between probability of penetration and impact velocity, V, was determined for each of the five missile masses.

b. Using the results of analysis (a), missile velocities, V_o, corresponding to zero probability of penetration were evaluated. The relation between threshold velocity and missile mass, m, was determined.

c. The results of the analyses described in (a) and (b) were combined to form a general equation expressing probability, P, as a function of m and V.

4.2 Impact Velocity vs Probability for Constant Missile Masses

Figure 4.1 is a graphical representation of the glass fragment penetration data recorded in Table 3.1. The logarithms of missile velocity were plotted on this chart against the probabilities of penetration. Allowing for a maximal variation in the probability of penetration of about 15 per cent, the data for each missile mass appeared by inspection to show a linear relationship between impact velocity and per cent penetration of the abdominal wall. Regression equations were determined which related the probability of penetra-

tion to impact velocity for the 5 different values of missile mass. These equations are recorded in Table 4.1, Equations 1 through 5, and are presented graphically in Figure 4.1 as dashed lines.

Since the slopes of the regression equations (expressed as the coefficient of P) were randomly distributed showing no dependence on missile mass, it was deemed advisable to substitute for the individual values the average value, 0.4842. This adjustment was made in such a way that the velocities for 0.5 probability of penetration were not changed. The adjusted regression equations are recorded in Table 4.1, Equations 6 through 10, and are plotted in Figure 4.1 as solid lines.

4.3   Threshold Velocities vs Missile Mass

The regression analyses made it possible to predict missile velocities as a function of probability of penetration for each of the 5 missile masses. Thus, using Equations 6 through 10, the velocities, V_o, corresponding to zero probability of penetration, were evaluated for each of the 5 groups of data representing different missile weights. It was found that a quasi-linear relation existed between the reciprocals of these threshold velocities and the logarithms of the corresponding values of missiles mass, as presented in Figure 4.2 which also shows a plot of the regression equation determined for the best fit to the 5 values obtained for $1/V_o$.   The equation obtained is shown below.

$$V_o = 329/(\log m + 2.3054) \qquad\qquad \underline{11}$$

where

V_o = threshold missile velocity, ft/sec

m = missile mass, gms

4.4 Probability of Penetration vs Missile Mass and Velocity

Equations 6 through 10 can be expressed in the following form:

$$\log V = \log V_o + 0.4842P \qquad \underline{12}$$

Equations 11 and 12 were combined to eliminate V_o. The resulting equation expressing probability of penetration in terms of missile mass and impact velocity was found to be:

$$\log V = 2.5172 - \log (\log m + 2.3054) + 0.4842P \qquad \underline{13}$$

This equation was solved for constant probability values of 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 and the results plotted in Figure 4.3. The experimental data from Table 3.1 are also shown on this graph. The agreement between the experimental data and the analytical results (Equation 13) was measured by the standard error of estimate which was found to be 0.0745. This means that approximately 2/3 of the probabilities are predicted by Equation 13 with errors not exceeding ±7.45 per cent.

CHAPTER 5

ANALYSIS OF FIELD DATA, METHOD 1

5.1 Missile Data and Objectives

In order to help assess the biological damage which might be expected from glass fragments occurring secondary to a nuclear explosion, the penetration criterion determined in Chapter 4 was applied to data from missile studies of Operation Teapot. The reader is referred to a previous report (5) for a detailed description of these studies.

The data used in the present study were obtained from missile traps placed inside houses approximately 10 ft behind windows facing ground zero, the houses being located at each of 3 ranges. The missile collecting area of each trap was about 3.5 sq ft. Six traps placed at 4,700 ft range (5.0 psi overpressure) collected 2129 missiles; 2 traps at 5,500 ft (3.8 psi) collected 320 and 5 traps at 10,500 ft (1.9 psi) collected 37 missiles. Ninety-eight per cent of the missiles collected by these traps were fragments of window glass and 2 per cent were glazing putty.

5.2 Expectation of Penetration Determined from Probability Evaluation for Each Missile

Using an enlarged chart similar to Figure 4.3 and the mass and velocity of each missile, the individual probability of penetration of the abdominal wall of the dog was determined. The probability values - 2486 in all - were then summed to find the expected number of penetrations for each range from ground zero. Expectation was expressed both as a percentage of the total missile sample and as missiles per sq ft expected to penetrate. The results of these

computations are shown in Table 5.1 marked with a single asterisk. It is of interest to note that at 5,500 ft range the expectation is 12.8 per cent (5.3 missiles per sq ft) while the expectation at 4,700 ft was only 3.9 per cent (3.9 missiles per sq ft). At 10,500 ft range the expectation was 0.4 per cent or 0.006 missiles per sq ft. These somewhat surprising results can be explained by the following generalizations:

a. The Nevada data showed that the mean missile velocity is less, but the mean missile mass greater at greater ranges from ground zero (5).

b. The probability of penetration is less for lower velocity, but is greater for heavier mass.

Thus, it is reasonable that the expectation of penetration would be greater for greater range from ground zero if the decreasing value of mean velocity were less significant than the increasing value of mean mass. This is evidently the case for the range interval between 4,700 and 5,500 ft, but not for the interval between 5,500 and 10,500 ft. This subject will be explored through quantitative analysis later.

CHAPTER 6

ANALYSIS OF FIELD DATA, METHOD 2

6.1 General Approach

The purpose of the study reported in this chapter was to determine how
the expectation of penetration varied with range from ground zero (or maximum
overpressure). In order to make a detailed study it was first necessary to
determine for ranges other than those used in the field study (a) the spatial
density of missiles, and (b) the percentage of these missiles within given velo-
city and mass intervals. Once (a) and (b) were determined, it was a relatively
simple procedure to apply the penetration criterion, Equation 13, to arrive at
an expected frequency of penetration.

The values of the spatial density of missiles for intermediate overpressure
regions were obtained by simple interpolation; however, the procedures neces-
sary to estimate the missile distributions according to mass and velocity were
much more involved. To accomplish the latter it was necessary to establish a
distribution model which would satisfy each of the 3 sets of field data; e.g.,
missiles collected at 4,700, 5,500 and 10,500 ft ranges. The model distribution
which was found to be satisfactory was the normal bivariate distribution of
missiles according to log mass and log velocity. The above distribution model
is completely defined by the appropriate means and standard deviations, pro-
vided that the variables are mutually independent.

Thus, the first step was to establish the independence of mass and velo-
city (paragraph 6.2). Next, various statistical parameters evaluated in the
previous study (5) were discussed and interpolated for intermediate over-

pressures (paragraph 6. 3). Then, the detailed computational procedure involved in arriving at an expectation of penetration was demonstrated for the 5 psi overpressure region (paragraph 6. 4). The results of such computations for 7 overpressure regions are presented in paragraph 6. 5.

6. 2   Independence of Velocity and Mass

It has been shown for the Nevada data on glass fragments (5) that the logarithms of missile mass and velocity were normally distributed. In order to construct a bivariate distribution using the above variables it was necessary to determine whether or not log velocity was independent of log mass. For this purpose, a regression analysis was performed for each of the 3 ranges, treating mass as the independent variable and velocity as the dependent one. In order to simplify the analysis, class intervals were used. The interval for mass was chosen to be 0. 2 common log units and for velocity 0. 1 units. Such class intervals were represented by small rectangles in Figure 6. 1. The numbers in the rectangles indicate percentage of the total missiles whose log masses and log velocities were within the respective class boundaries.

The regression equations for the 3 groups of data were found to be:

4, 700 ft range -

$$V = 168. 1 \, m^{-0.0060}$$ <u>14</u>

5, 500 ft range -

$$V = 168. 7 \, m^{0.0138}$$ <u>15</u>

10, 500 ft range -

$$V = 101. 0 \, m^{-0.0374}$$ <u>16</u>

where

> V = missile velocity in ft/sec
>
> m = missile mass in gms

These equations, as well as the standard errors of estimate, were plotted in Figure 6.1.

The exponent on m denotes the slope of the regression curve and thus the dependence of velocity on mass — complete independence of the two variables would be indicated by a zero slope. When the sizes of missile samples are compared with the slopes — Equation 14, 2129 missiles, -0.0060 slope; Equation 15, 320 missiles, 0.0138 slope; Equation 16, 37 missiles, -0.0374 slope — it is evident that slopes tend to converge about zero as the sample size increases. Thus, it was concluded that the velocities of glass fragment missiles are not related to their masses in any significant fashion.

Other data indicated in Figure 6.1 will be discussed in the next paragraph.

6.3 Statistical Parameters

The employment of the logarithmic transformation mentioned above involves statistical parameters somewhat different from those ordinarily used (5, 7, 8). The logarithm of the geometric mean, employed in this study, is equal to the arithmetic mean of the logarithms. Correspondingly, the logarithm of the standard geometric deviation is the standard deviation of the logarithms. In general, statistical manipulations are carried out in the ordinary way except that the logarithms of quantities are used rather than the quantities themselves.

The geometric mean masses and velocities and the corresponding standard geometric deviations are presented in Table 5.1 for the missiles collected

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at the 3 ranges from ground zero (5). Also shown in this table are the average

spatial missile densities and the maximum overpressures measured at these

ranges. The geometric means and spatial densities of missiles were plotted

in Figure 6.2 as a function of overpressure. The various points were connected

by straight lines since the "true" curves were not known. The standard errors

of the mean plotted as dashed lines indicate that the accuracy of measurement

increases with overpressure.

Thus, the curves shown in Figure 6.2 made it possible to interpolate the

various parameters for overpressure values between 1.9 and 5.0 psi. However,

since the standard geometric deviations showed no significant trend for the 3

distributions, the following weighted averages were used for the entire range in

overpressures:

Standard geometric deviation in mass: 3.074

Standard geometric deviation in velocity: 1.267

For illustrative purposes the geometric mean mass and velocity and the

respective standard deviations were plotted on Figure 6.1 for the 3 bivariate

distributions. Agreement between the 2 computational procedures is indicated

by the proximity of the geometric means to the regression curves. In each

case the plotted standard geometric deviations in velocity include intervals of

almost the same magnitude as that of the standard error of estimate.

Also for illustrative purposes, each of the 3 plots shown in Figure 6.1

includes constant probability of penetration lines of values 0, 0.5, and 1.0.

The relative portions of the 3 distributions lying within the probability "field"

are roughly indicated by the positions of the respective geometric means. It

is significant from the standpoint of expected percentage penetrations that the

only geometric mean which is itself within the probability field is that for the 5,500 ft range missiles (see paragraph 5.2).

6.4 Computation of the Expectation of Penetration for the 5 psi Overpressure Region (4,700 ft Range)

The normal model distribution of missiles for the 5 psi region was computed from the following statistical parameters:

   Geometric mean mass = 0.133 gms

   Average standard geometric deviation in mass = 3.074

   Geometric mean velocity = 170 ft/sec

   Average standard geometric deviation in velocity = 1.267

The first step was to obtain the distribution of missiles according to log mass. The log mass range from -1.6 (0.0251 gms) to 1.0 (10.0 gms) was divided into intervals of 0.2 log units - see Table 6.1. The next 2 operations involved the determination of the deviation of each class boundary from the mean in standard deviation units: $(\log m - \log \bar{m}) / \log \bar{s}$. Then, by use of a table of normal areas (8), the percentages of the sample, P_m, between given class boundaries and the mean were evaluated. The percentage of the sample found within a given interval, ΔP_m, was then determined by the difference between the interval's boundary percentage values.

The second step was to determine the distribution of missiles according to log velocity. The procedure was the same as that described above except that class intervals were chosen to be 0.1 log units. The results of these computations are presented in Table 6.2.

Since the distributions computed above had been shown to be independent (paragraph 6.2) they were used as marginal distributions to construct a single

bivariate distribution. The frequency in any given bivariate class interval was determined by multiplying the frequency for the log mass interval (ΔP_m, Table 6.1) by the frequency for the log velocity interval (ΔP_v, Table 6.2). The results of these computations were presented both in tabular and graphical forms — Table 6.3 and Figure 6.3. The height of the blocks in Figure 6.3 represents the percentage of the missile sample, or frequency, to be found within the given class boundaries. The percentages thus represented are the most probable frequencies for this distribution model and would, of course, deviate somewhat from those measured in a finite sample. The distribution of missiles with masses less than 0.0251 gms was not computed since — as it will be shown later — they made no contribution to the expectation of penetration.

Having computed the most probable frequency of missiles for various class intervals, the next operation was to determine for the same intervals the probability of penetration into the abdomen of a dog. Equation 13 was used to determine probabilities at the 4 corners of each bivariate interval. The probability for a given interval was assumed to be the average of the 4 corner values. These average probabilities are presented in Table 6.4 and in Figure 6.4.

The expected frequency of missile penetrations was then computed for each bivariate class interval by multiplying missile frequency values found in Table 6.3 by the corresponding probability values in Table 6.4. The results of these calculations are shown in Table 6.5 and are displayed graphically in Figure 6.5. Summation of the individual expectations indicated that 4.26 per cent of the missile sample can be expected to penetrate the abdomen of a dog. Since the average spatial density of missiles at 5 psi was 100.9 missiles/ft^2 (Table 5.1, Figure 6.2), the number of missiles per sq ft expected to pene-

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trate was 4.30.

6.5 Computed Expectations of Penetration for Various Overpressure Regions

Computations similar to those described in paragraph 6.4 were made for distributions corresponding to the following overpressure values: 2.0, 3.0, 3.5, 3.7, 4.0, 4.5, and 5.0 psi. The results of these computations, recorded in Table 6.6 and plotted in Figure 6.6, indicate that the expected percentage penetrations reached a maximum at an overpressure of about 3.7 psi and that the expected penetrations per sq ft was maximum at an overpressure of about 3.9 psi.

CHAPTER 7

DISCUSSION

7.1 General

The objective of this study was to assess, so far as possible, the biological implications of glass fragmented and set in motion by atomic explosions when the mass and velocity of the individual fragments are known for a given set of circumstances. It was necessary, first, to adopt a biological criterion capable of definition with an accuracy at least equal to that of the determination of the mass and velocity of the missiles collected in the field and, second, to utilize statistical concepts in a manner which not only would allow generalizations on an "average" basis, but would quantitatively express the reliability associated with the analytical results obtained.

In previous tests the abdominal wall of anesthetized dogs was used as a target for artificial missiles which varied widely in mass and velocity. The diameter of the impact area, however, was always the flat circular surface of a cylinder (6). Under such circumstances the standard deviation obtained in determining conditions critical for penetration of the abdominal wall of the dog was about 8 per cent while the standard deviation of the determination of velocity for the glass fragments collected by the use of traps in the Nevada field study was 10.5 per cent. Thus, it was assumed that a similar penetration study using fragments of glass as missiles would yield a penetration criterion at least as accurate as the velocity data for the field missiles. This assumption proved to be correct - the standard deviation for the penetration criterion was computed to be 7.45 per cent while that for velocity determinations of

field missiles, as stated above, was 10.5 per cent.

7.2   Velocity

The ability of the air gun to reproduce the desired velocities is indicated by the standard deviation and range in velocities noted for each series of shots recorded in Columns C and D of Table 3.1. In order to ascertain whether or not deviations in velocity for a given series contributed to the variability of the penetration data, the average velocity of only the penetrating missiles was computed for series 1, 8, and 11 (see Column H). Deviation of these average velocities so computed from those for the entire series was in no case greater than 2 ft/sec. Thus, it appears that variations in probability of penetration cannot be ascribed to deviations of velocity.

7.3   Penetration Data

It is obvious that the probability of penetration of a given glass missile depends not only on its mass and velocity but also upon such variables as missile shape, missile orientation at impact, and biological alterations in the target. Attempts were made in this study to hold mass and velocity as constant as possible for every series of shots, and to use uniform dogs for the entire study. On the other hand, missile shape and orientation were randomized in order to duplicate as nearly as possible the missiles resulting from an explosion. The degree of randomness actually attained is no doubt reflected in the regularity of the pattern which the penetration data (Table 3.1, Column G) forms with the missile mass and velocity data. The pattern for these data is presented in Figure 3.3. The computed standard error of estimate indicated that over 2/3 of the 16 probability values agreed with the overall pattern within ±7.45 per cent.

The examination of the 2 probability values showing the least agreement with the general pattern — those for series 8 and 9, Table 3.1, is particularly interesting. The probability determined for series 8 was 62.5 per cent — 15.5 per cent higher than that predicted by the results of the entire experiment as represented by Equation 13. The standard deviation computed for this probability value was 7.7 per cent; thus, the deviation from the predicted value was 2.0 standard deviations. This means that if the probability for series 8 were evaluated by repeated experiments, 5 per cent of the values thus obtained would have deviations as great as the one determined in this study. Similarly, the deviation for series 9 was found to be 1.4 standard deviations. A deviation as great as this would occur 16 per cent of the time for similar experiments. If the data for series 8 and 9 are combined, one obtains a "new" average velocity of 362.7 ft/sec, and an average probability of penetration of 63.0 per cent with a standard deviation of 5.4 per cent. Equation 13 predicts for this average velocity (362.7 ft/sec) and mass (0.318 gms) a probability of penetration of 62.0 per cent. Thus, the deviation of the probability value for the combination of series 8 and 9 from the predicted value is only 0.2 standard deviation.

7.4   Extrapolation of Penetration Data

In deriving the criterion of the probability of penetration, the largest test missiles used had an average weight of 1.895 gms. In order to apply this criterion to field data, it was necessary to extrapolate probabilities for masses as large as 10 gms. Computations were made to determine what effect this procedure could have on the results. Expressing expectation as a percentage of the missile sample, the "total" expectation of penetration and the expectation for missiles larger than 2.5 gms for various overpressure regions were:

Maximum Overpressure	Missiles Expected to Penetrate	Missiles Larger than 2.5 gms Expected to Penetrate
5 psi	4.3 per cent	0.1 per cent
4 psi	11.8 per cent	2.1 per cent
3 psi	9.2 per cent	3.3 per cent
2 psi	3.4 per cent	2.1 per cent

The above table shows to what extent the figures for expected penetrations are dependent upon the extrapolation of the penetration criterion for missiles whose masses were greater than 2.5 gms. For the 5 psi overpressure region, 4.3 per cent of all missiles were expected to penetrate, but the portion of this figure involving the larger missiles was only $0.1/4.3 = 0.023$. Similar calculations for the 4, 3, and 2 psi regions were 0.18, 0.36 and 0.62, respectively. Thus, it can be surmised from the above - and also from the fact that the sizes of the samples of missiles were smaller in the lower pressure regions - that the reliability of the figures for expected penetrations is less for the lower overpressure regions.

7.5   Expectation of Penetration

Two statistical arguments were followed in applying the penetration equation (or the chosen biological criterion) to the physical data obtained in the field missile study. The first method is direct, specific and by far the simpler of the two. Since the mass of any glass missile gathered in the field study was known and the corresponding velocity had been determined within ±10.5 per cent (5), it was not difficult to use these parameters and Figure 3.1 to assign a value for probability of penetration to each individual missile caught at each of the 3 ranges from ground zero; i.e., 4,700, 5,500, and 10,500 ft corres-

ponding to overpressures of 5, 3.8 and 1.9 psi, respectively.

It must be emphasized that this solution is specific in that it applies to a 30-35 KT device at the stated ranges and is meant to carry only such biological meaning as warranted by the nature of the biological target used to define the penetration criterion.

The second method was more complex, but much more general not only in that predictions at intermediate ranges (or various maximum overpressures) could be made but in that better accuracy was gained in formulating statistical expressions derived from a normalization of the massed data.

Expected percentage penetrations were estimated for the 1.9, 3.8, and 5.0 psi regions by the 2 different methods. The agreement between the results obtained by the 2 methods, illustrated in Figure 6.6, seems reasonable for the 5.0 and 3.8 psi regions. The rather large discrepancy (2.5 per cent) indicated for the 1.9 psi region is probably due to the small sample of 37 missiles available at this pressure.

7.6   Interpretation

The prediction apparent in Figure 6.6; namely, that there is an optimal range from ground zero at which penetration of the dog's abdomen is maximal, rests basically upon: (1) empirical data obtained at 3 ranges, using a device of 30-35 KT yield, and (2) the assumption that interpolations of data for missile mass and velocity at intermediate ranges will not involve a significant error. From the available data one cannot support a statement that the same result will be obtained for nuclear explosions varying widely in yield, although this seems a likely possibility. Fortunately, it will be possible to check the relation of penetration probability to overpressure in future field tests, a study which certainly should be accomplished.

7.7 Biological Implications

The authors are unaware of any reliable data which allows the penetration data obtained on dogs to be applied to the human case. However, the use of the penetration criteria for experimental animals to attempt to predict injury to the civilian and military population will underestimate the damaging potential of glass fragments. This is so because of the possibilities of injuries to the eyes and the rather serious implications of multiple puncture wounds of the skin, which in a major nuclear explosion will involve other complicating factors, such as dust, dirt and other debris (9), bacterial contamination, radioactive particulate material and no doubt a rather significant incidence of radiation and thermal injury within its general debilitating effects on the human target.

CHAPTER 8

SUMMARY

A study was made on Operation Teapot of missiles produced secondary to blast (5), particular attention being given to mass, velocity, and spatial density of glass missiles originating from shattered windows. The present exploratory study was made to interpret biologically the data obtained in Nevada. The index of biological damage was arbitrarily chosen to be the penetration of a fragment of glass into the abdomen of a dog. Accordingly, a study in the laboratory was made to determine a penetration criterion which was then applied to the Nevada field data to determine the number of glass fragments originating from a window which could be expected to penetrate the abdomen of a dog.

In the laboratory phase of the study 389 window glass fragments of 5 average weights from 0.0543 to 1.895 gms were shot from an air gun at the abdomen of anesthetized dogs at 16 average velocities ranging from 170 to 858 ft/sec. These data when analyzed resulted in the following penetration criterion which expresses the relation between probability of penetration, mass, and velocity for glass fragments of random shapes and impact orientations:

$$\log V = 2.5172 - \log (\log m + 2.3054) + 0.4842P$$

where

V = missile velocity, ft/sec

m = missile mass, gms

P = probability of penetration

The above equation was then applied to missile data which had been

obtained on Operation Teapot. The probability of penetration was evaluated for 2486 glass missiles collected in traps placed in houses at various ranges from ground zero. Data used in this study were for missiles originating from windows facing ground zero and collected in traps about 10 ft from the windows. It was found that 3.9 per cent of such missiles at 4,700 ft range (5.0 psi maximum overpressure) could be expected to penetrate the abdomen of a dog. Similarly, the expectations of penetration at 5,500 ft (3.8 psi) and 10,500 ft (1.9 psi) were 12.8 and 0.4 per cent, respectively. In terms of missiles per sq ft, the expectations of penetration for the 3 ranges — 4,700, 5,500, and 10,500 ft — were 3.9, 5.3, and 0.006, respectively.

The Teapot Operation missile data were then used to construct model missile distributions according to log mass and log velocity. The parameters of such model distributions — geometric mean missile mass and velocity and standard geometric deviations — were evaluated, by interpolation, for various pressure regions between 1.9 and 5.0 psi. This made it possible to compute expectation of penetration as a function of maximum overpressure. The results of these computations showed that the expectation of penetration for overpressure regions between 1.9 and 5.0 psi was maximum at about 3.8 psi. These results essentially agreed with those discussed in the last paragraph.

Included in Chapter 7 was a discussion expressing words of caution concerning (a) the application of the penetration data to the human case, and (b) the general applicability of the missile data in those instances involving nuclear explosions varying widely in yield.

Table 2.1   Experimental Design Showing Five Groups Segregated
            According to Average Missile Mass and the Average
            Missile Velocities Employed in Each Group.   The mass
            of the glass fragments were within ±5 per cent of those
            indicated.   For variation in the missile velocities see
            Table 3.1.

Experimental Groups According to Missile Mass and Average Missile
            Velocities in ft/sec Used in Each Series

I 0.0543 gms	II 0.131 gms	III 0.318 gms	IV 0.769 gms	V 1.895 gms
487	205	192	200	170
858	262	305	297	240
	456	419	418	360
	649			387

Table 3.1   Laboratory Data for the Determination of Penetration Criterion
for the Abdomen of Dogs

Group	Series	A Dog No.	B Average Missile Mass* (gms)	C Ave. Missile Velocity and Std. Deviation (ft/sec)	D Range of Missile Velocity (ft/sec)	E Number of Shots	F Per cent Penetrating Skin	G Per cent Penetrating Abdomen and Std. Deviation	H Ave. Velocity of Penetrating Missiles (ft/sec)
I	1	C-14	0.0543	487 ± 8.8	+16, -17	25	52	36.0 ± 9.6	489
	2	C-12	0.0543	858 ± 11.6	+24, -26	25	100	88.0 ± 6.5	
II	3	C-7	0.131	205 ± 3.9	+7, -8	25	12	4.0 ± 3.9	
	4	C-8	0.131	262 ± 10.9	+13, -44	25	52	0	
	5	C-9	0.131	456 ± 11.4	+19, -21	25	88	60.0 ± 9.8	
	6	C-13	0.131	649 ± 10.9	+17, -23	26	100	92.3 ± 5.3	
III	7	C-3 C-8	0.318	192 ± 4.0	+11, -8	26	54	11.5 ± 6.4	
	8	C-2	0.318	305 ± 8.2	+16, -15	40	82	62.5 ± 7.7	304
	9	C-7 C-1	0.318	419 ± 9.6	+16, -27	41	95	63.4 ± 7.5	
IV	10	C-4	0.769	200 ± 3.8	+8, -7	24	62	25.0 ± 8.8	
	11	C-5	0.769	297 ± 4.9	+9, -10	25	88	60.0 ± 9.8	298
	12	C-6	0.769	418 ± 10.4	+25, -28	25	100	88.0 ± 6.5	
V	13	C-10	1.895	170 ± 2.8	+5, -4	21	33	14.3 ± 7.6	
	14	C-9 C-10	1.895	240 ± 9.3	+32, -10	19	79	68.4 ± 10.7	
	15	C-12	1.895	360 ± 6.3	+10, -10	7	100	100	
	16	C-11	1.895	387 ± 4.5	+10, -6	10	100	100	

*Range of Missile Mass was ± 5 per cent.

Table 4. 1 Regression Equations Expressing Probability of Penetration for Various Sizes of Glass Fragment Missiles. See Figure 3. 1.

m = missile mass, gms

V = missile velocity, ft/sec

P = probability of penetration $(0 < P < 1.0)$

Equation No.	m	Regression Equations
1	0. 0543	$\log V = 2.5172 + 0.4731\ P$
2	0. 131	$\log V = 2.3576 + 0.4933\ P$
3	0. 318	$\log V = 2.2214 + 0.5281\ P$
4	0. 769	$\log V = 2.1723 + 0.5075\ P$
5	1. 895	$\log V = 2.1390 + 0.4190\ P$

Equation No.	m	Regression Equations adjusted to an average slope
6	0. 0543	$\log V = 2.5116 + 0.4842\ P$
7	0. 131	$\log V = 2.3621 + 0.4842\ P$
8	0. 318	$\log V = 2.2433 + 0.4842\ P$
9	0. 769	$\log V = 2.1840 + 0.4842\ P$
10	1. 895	$\log V = 2.1064 + 0.4842\ P$

Table 5.1 Statistical Parameters and Predicted Penetration Data
for Missiles from Traps at Various Ranges from Ground
Zero

	4,700	5,500	10,500
Distance from Ground Zero, ft	4,700	5,500	10,500
Maximum overpressure, psi	5.0	3.8	1.9
Number of traps	6	2	5
Total number of glass missiles	2129	320	37
Geometric mean missiles mass, gms	0.133	0.580	1.25
Standard geometric deviation in mass	3.01	3.47	3.35
Geometric mean missile velocity, ft/sec	170	168	103
Standard geometric deviation in velocity	1.27	1.25	1.25
Per cent of total missiles expected	3.9*	12.8*	0.4*
to penetrate	4.3**	13.7**	2.9**
Average number of missiles per sq ft	100.9	45.5	2.1
Missiles per sq ft expected to penetrate	3.9*	5.3*	0.006*
	4.3**	6.1**	0.03**

*Computed from individual evaluation of each missile
**Computed from model missile distributions

Table 6.1   Marginal Distribution of Missiles According to Log Mass

Maximum Overpressure = 5 psi

m = mass class boundary in ft/sec

$\overline{m}$ = geometric mean mass = 0.133

$\overline{s}$ = average standard geometric deviation = 3.074

P_m = percentage of missile sample whose masses have values between m and $\overline{m}$, determined from tables of normal areas

ΔP_m = percentage of missile sample whose masses have values between the given class boundaries

log m	m	log m - log $\overline{m}$	$\dfrac{\log m - \log \overline{m}}{\log \overline{s}}$	P_m	ΔP_m
-1.6	0.0251	-0.7239	-1.49	43.189	
					7.20
-1.4	0.0398	-0.5239	-1.08	35.993	
					11.46
-1.2	0.0631	-0.3239	-0.66	24.537	
					14.67
-1.0	0.100	-0.1239	-0.25	9.871	
					16.23
-0.8	0.158	0.0761	0.16	6.356	
					15.21
-0.6	0.251	0.2761	0.57	21.566	
					12.08
-0.4	0.398	0.4761	0.98	33.646	
					8.13
-0.2	0.631	0.6761	1.39	41.774	
					4.63
0	1.000	0.8761	1.80	46.407	
					2.24
0.2	1.585	1.0761	2.21	48.645	
					0.91
0.4	2.512	1.2761	2.62	49.560	
					0.32
0.6	3.981	1.4761	3.03	49.878	
					0.09
0.8	6.310	1.6761	3.44	49.971	
					0.02
1.0	10.000	1.8761	3.85	49.994	

Table 6.2   Marginal Distribution of Missiles According to Log Velocity

Maximum overpressure = 5 psi

V = velocity class boundary in ft/sec

$\overline{V}$ = geometric mean velocity = 170 ft/sec

$\overline{s}$ = average standard geometric deviation = 1.267

P_v = percentage of missile sample whose velocities have values between V and $\overline{V}$, determined from tables of normal areas

ΔP_v = percentage of missile sample whose velocities have values between the given velocity class boundaries

log V	V	log V - log $\overline{V}$	$\dfrac{\log V - \log \overline{V}}{\log \overline{s}}$	Pv	ΔP_v
2.0	100.0	-0.2304	-2.24	48.745	
					8.95
2.1	125.9	-0.1304	-1.27	39.796	
					28.00
2.2	158.5	-0.0304	-0.30	11.791	
					36.97
2.3	199.5	0.0696	0.68	25.175	
					19.88
2.4	251.2	0.1696	1.65	45.053	
					4.51
2.5	316.2	0.2696	2.62	49.560	
					0.44
2.6	398.1	0.3696	3.60	50.000*	

*The distribution is assumed to terminate at this class boundary.

Table 6.3 Normal Model Distribution of Glass Fragment Missiles According to Log Mass and Log Velocity

Maximum overpressure ≒ 5 psi

Figures represent percentage of sample expected within given class boundaries

Mass, gms ↓ \ Velocity, ft/sec →	100.0	125.9	158.5	199.5	251.2	316.2	398.1
0.0251							
	0.64	2.02	2.66	1.43	0.32	0.03	
0.0398							
	1.02	3.22	4.26	2.29	0.52	0.05	
0.0631							
	1.31	4.12	5.44	2.93	0.66	0.06	
0.100							
	1.44	4.54	5.99	3.22	0.73	0.06	
0.158							
	1.35	4.26	5.62	3.02	0.68	0.06	
0.251							
	1.08	3.39	4.48	2.41	0.54	0.05	
0.398							
	0.72	2.27	3.00	1.61	0.36	0.03	
0.631							
	0.41	1.29	1.70	0.92	0.21	0.02	
1.000							
	0.20	0.61	0.81	0.44	0.10	0.01	
1.585							
	0.08	0.25	0.33	0.18	0.04	0	
2.512							
	0.03	0.08	0.11	0.06	0.01	0	
3.981							
	0.01	0.03	0.04	0.02	0	0	
6.310							
	0	0	0	0	0	0	
10.000							

Table 6.4 Probability of Penetration of Glass Fragment Missiles Averaged Over Increments of Mass and Velocity.
Target: Abdomen of Dogs

Mass, gms ↓ \ Velocity, ft/sec →	100.0	125.9	158.5	199.5	251.2	316.2	398.1
0.0251	0	0	0	0	0	.021	
0.0398	0	0	0	0	.014	.099	
0.0631	0	0	0	0	.064	.230	
0.100	0	0	0	.031	.165	.368	
0.158	0	0	.008	.098	.284	.491	
0.251	0	0	.040	.183	.390	.596	
0.398	0	.003	.090	.278	.484	.691	
0.631	0	.027	.157	.363	.570	.776	
1.000	0	.066	.235	.441	.648	.820	
1.585	.008	.109	.294	.513	.719	.874	
2.512	.032	.166	.373	.579	.786	.945	
3.981	.062	.219	.435	.641	.848	.975	
6.310	.093	.286	.492	.699	.896	.995	
10.000							

Table 6.5 Expected Missile Penetrations for Given Log Mass and Log Velocity Intervals.

Maximum overpressure: 5 psi

Figures represent percentage of total missile sample expected to penetrate within given class boundaries
Total Expectation: 4.3 per cent

Velocity, ft/sec ⟶

Mass, gms ↓	100.0 — 125.9	125.9 — 158.5	158.5 — 199.5	199.5 — 251.2	251.2 — 316.2	316.2 — 398.1
0.0251 — 0.0398	0	0	0	0	0	.001
0.0398 — 0.0631	0	0	0	0	.007	.005
0.0631 — 0.100	0	0	0	0	.042	.014
0.100 — 0.158	0	0	0	.100	.120	.018
0.158 — 0.251	0	0	.045	.296	.193	.029
0.251 — 0.398	0	0	.179	.441	.168	.030
0.398 — 0.631	0	.007	.270	.448	.174	.020
0.631 — 1.000	0	.035	.267	.334	.120	.016
1.000 — 1.585	0	.041	.190	.194	.065	.008
1.585 — 2.512	.001	.027	.097	.092	.029	0
2.512 — 3.981	.001	.013	.041	.035	.008	0
3.981 — 6.310	.001	.007	.017	.013	0	0
6.310 — 10.000	0	0	0	0	0	0

Table 6.6 Expectations of Penetration Determined from
Model Missile Distributions for Various Over-
pressure Regions

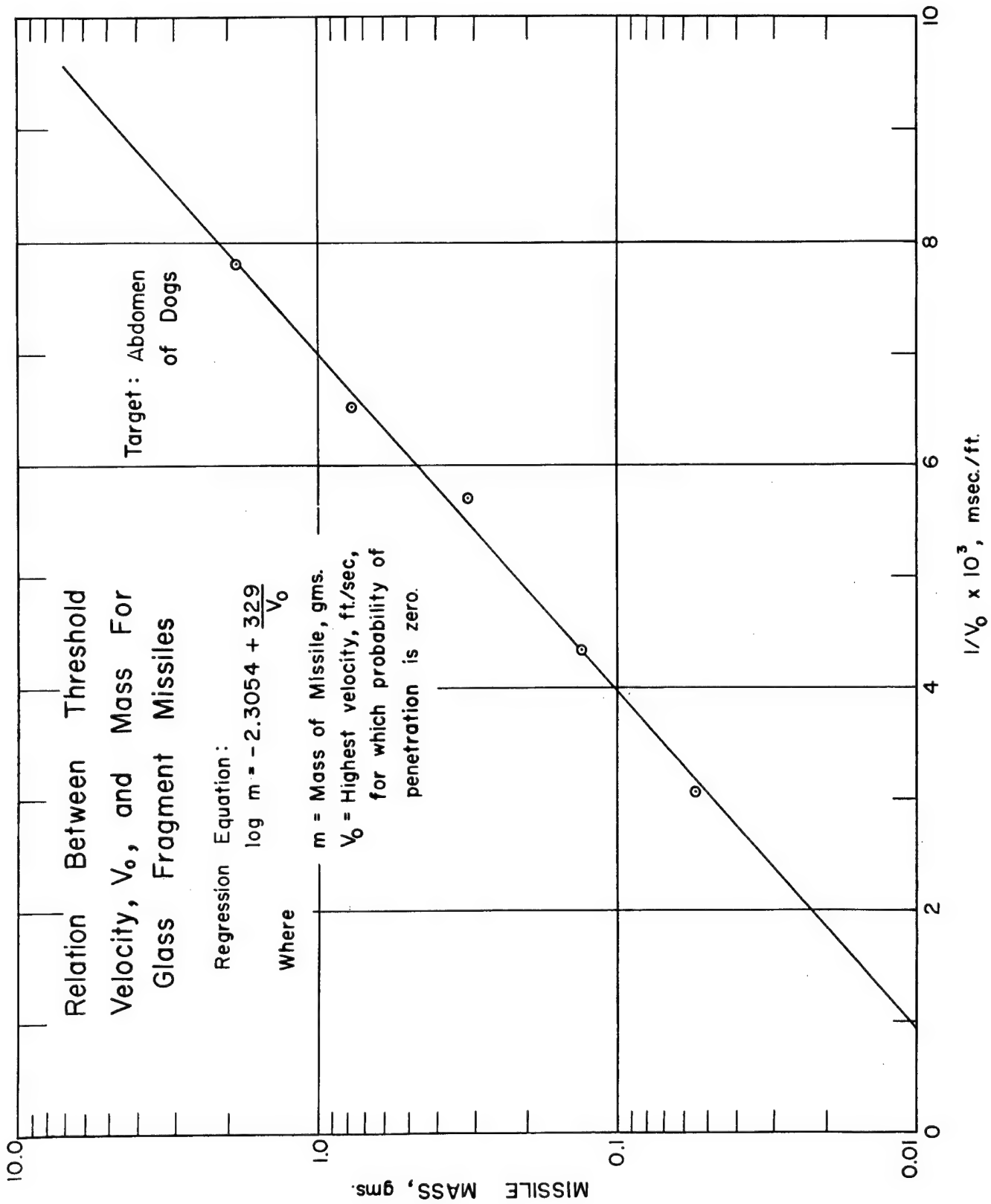| Overpressure Region, psi	2.0	3.0	3.5	3.7	4.0	4.5	5.0
Expected percentage penetrations	3.42	9.17	12.66	13.78	11.78	7.30	4.26
Expected penetrating missiles per sq ft	0.09	1.47	3.99	5.51	6.24	5.33	4.30

Fig. 4.1
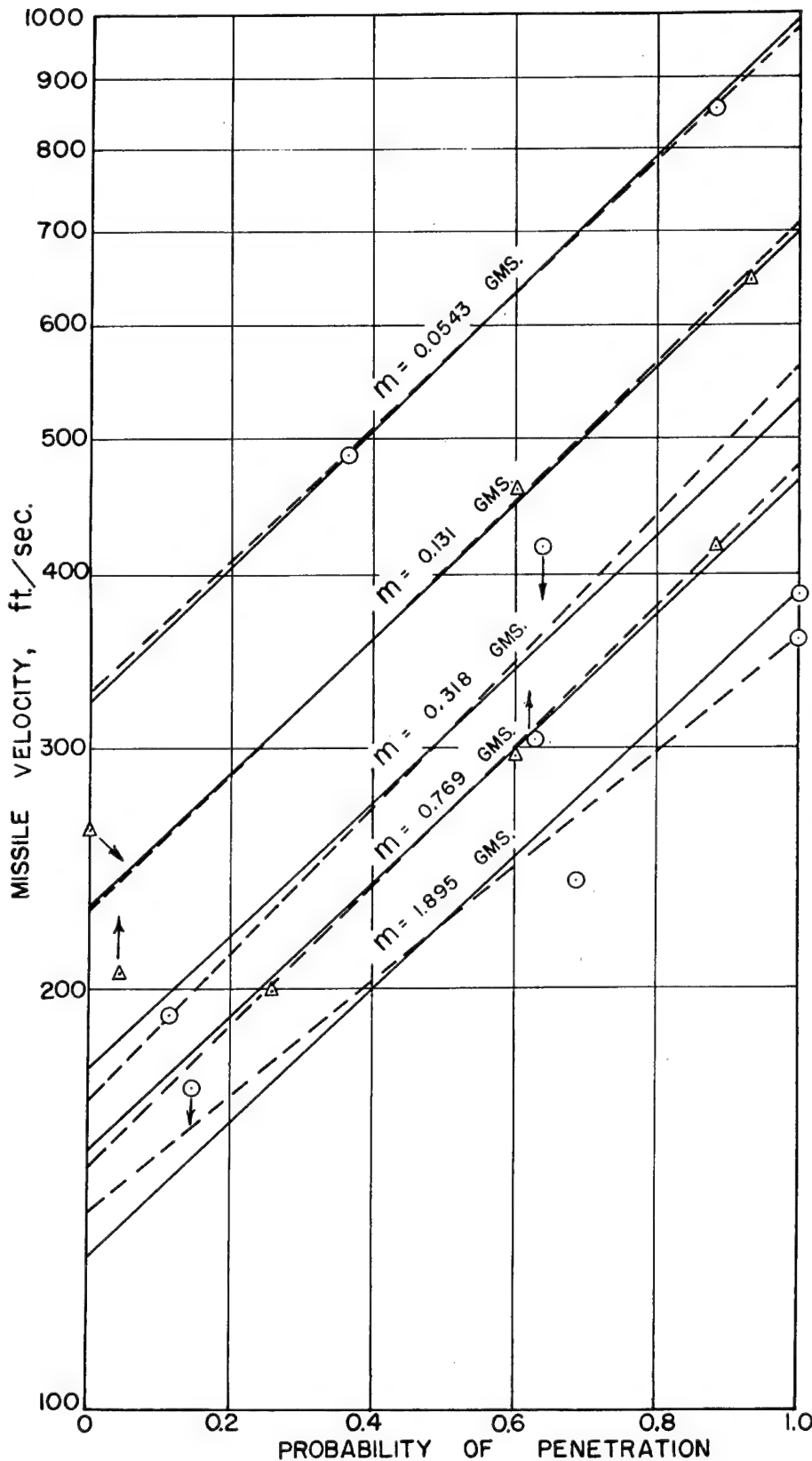
Probability of Penetration as a Function of Velocity for Various Sizes of Glass Fragment Missiles. Target: Abdomen of Dogs.

DASHED LINES: REGRESSION CURVES FOR GIVEN MASS VALUES.

SOLID LINES: REGRESSION CURVES ADJUSTED TO AN AVERAGE SLOPE

Fig. 4.2

Relation Between Threshold Velocity, V_o, and Mass For Glass Fragment Missiles

Target: Abdomen of Dogs

Regression Equation:

$$\log m = -2.3054 + \frac{329}{V_o}$$

Where

m = Mass of Missile, gms.

V_o = Highest velocity, ft/sec, for which probability of penetration is zero.

MISSILE MASS, gms.

$1/V_o \times 10^3$, msec./ft.

Fig. 4.3

Probability of penetration of glass fragments into the abdomen of a dog as a function of missile mass and impact velocity.

Equation: $\log V = 2.5172 - \log (\log m + 2.3054) + 0.4842\, P$

where V = impact velocity in ft/sec
m = mass of glass fragments in gms
P = probability of penetration

Standard Error of Estimate: 0.0745

BAIRD MEMORIAL RESEARCH LABORATORY
Lovelace Foundation for Medical Education and Research
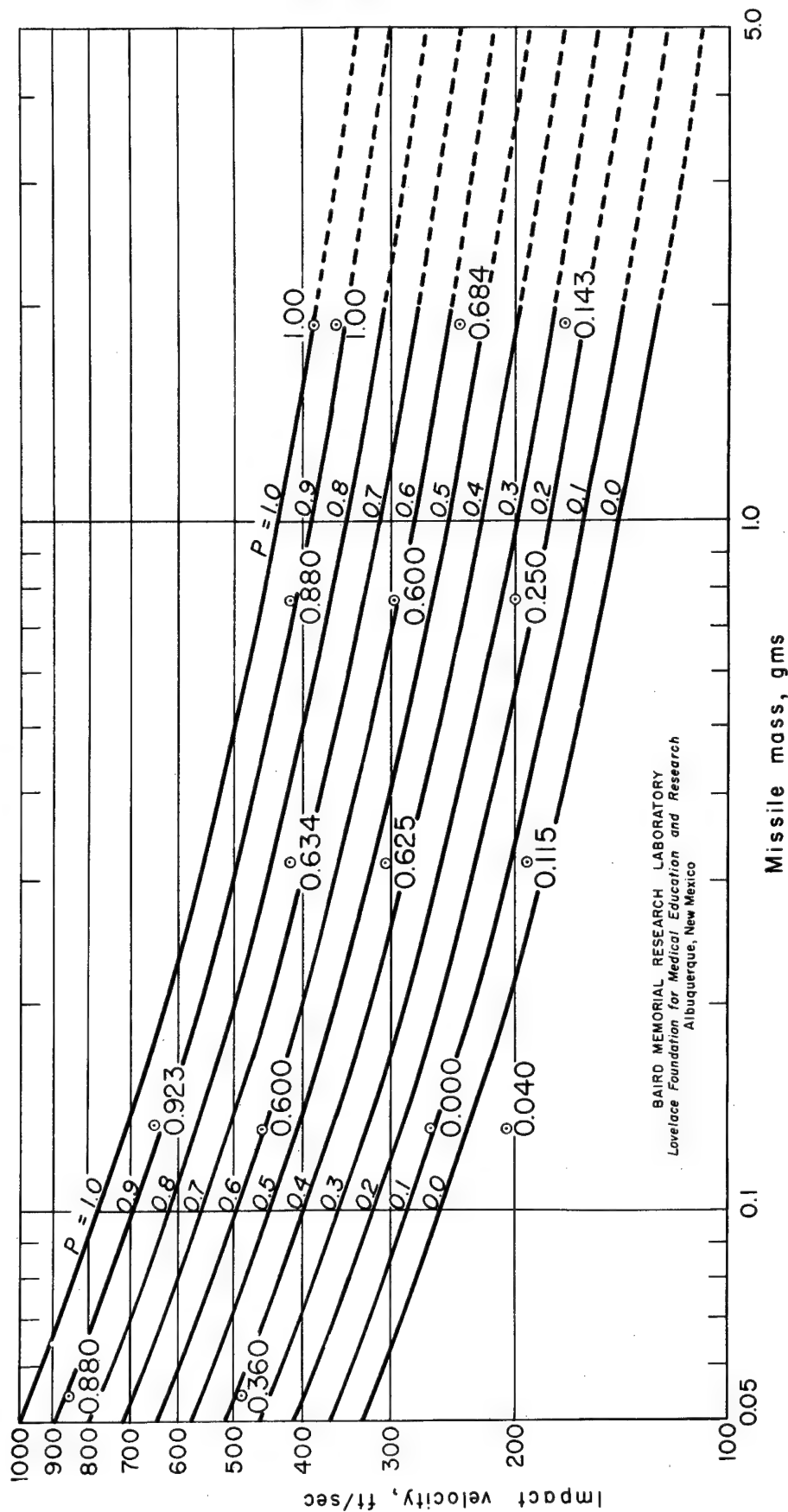Albuquerque, New Mexico

Fig. 6.1

Distribution of Glass Fragment Missiles According to Log Mass and Log Velocity at Ranges of 4700 ft, 5500 ft, and 10,500 ft. from Ground Zero

Small Rectangles Indicate Class Boundries

Numbers in Rectangles Indicate Percent of Total Missiles

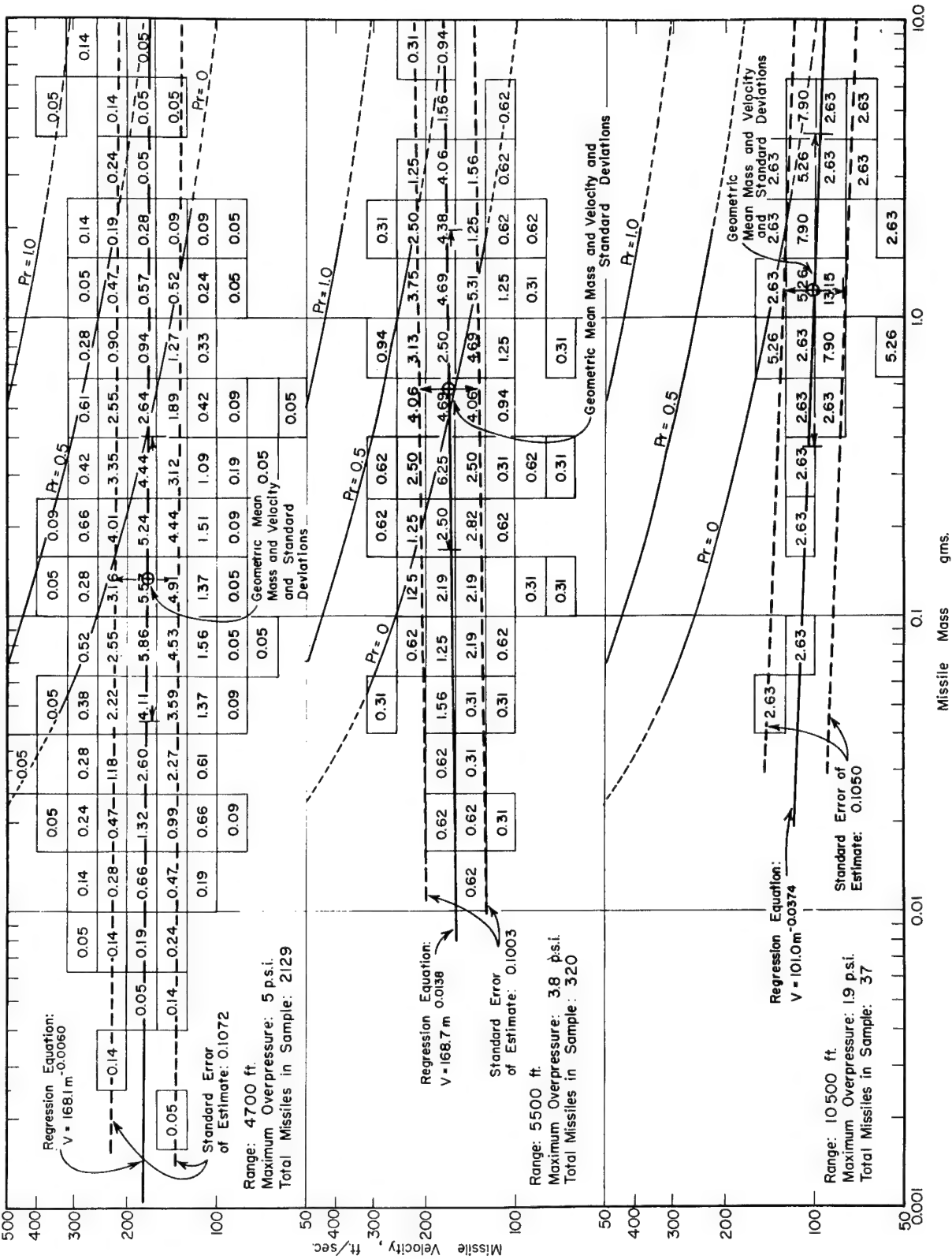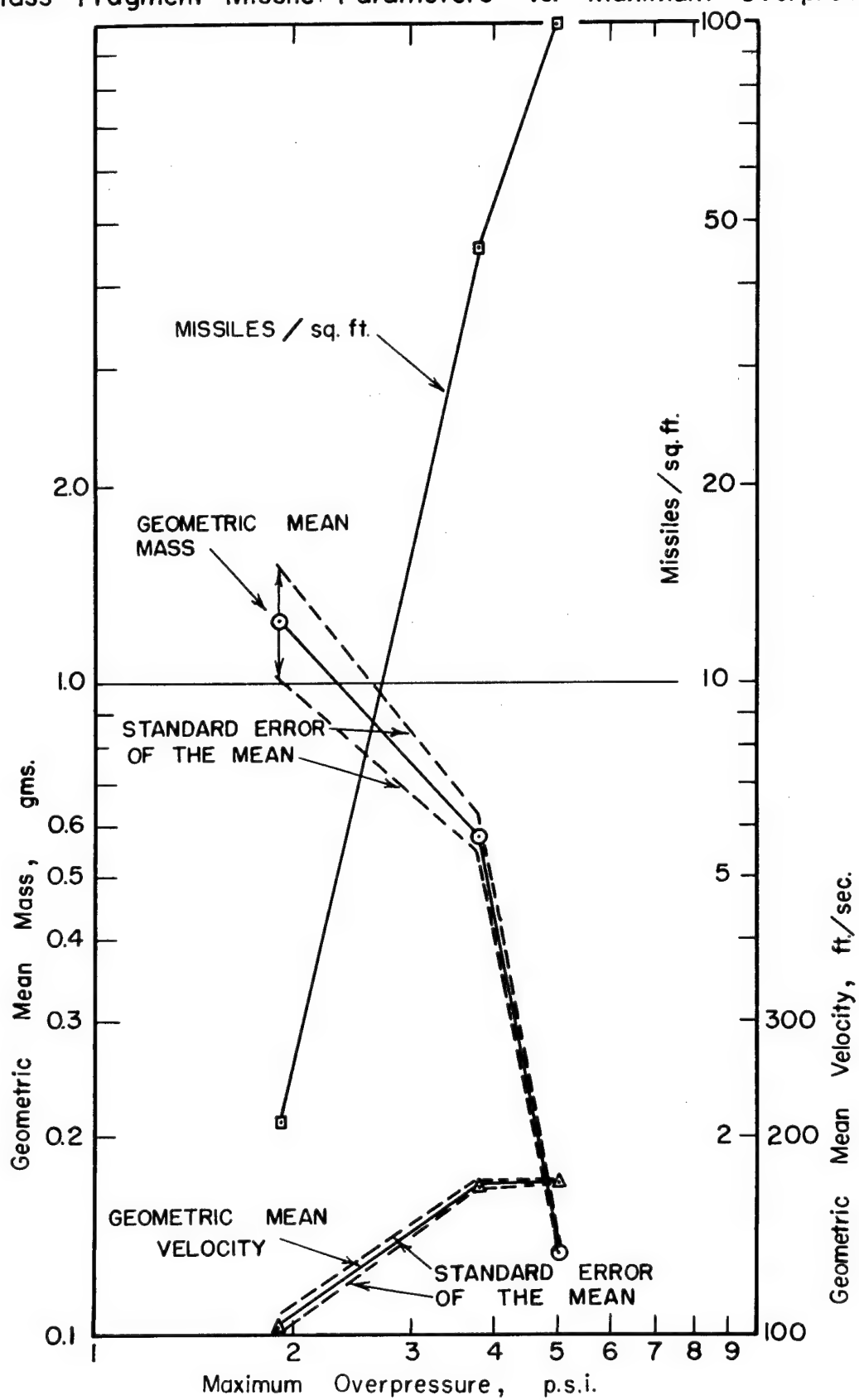Pr Lines Indicate Probability of Penetration of the Abdomen of Dogs

Fig. 6.2

Glass Fragment Missile Parameters vs. Maximum Overpressure

Fig. 6.3

Normal Model for the Distribution
of Glass Fragment Missiles
According to Log Mass & Log Velocity

Overpressure Region: 5 psi

Geometric Mean Mass: 0.133 gms

Standard Geometric Deviation in Mass: 3.074

Geometric Mean Velocity: 170 ft/sec

Standard Geometric Deviation in Velocity: 1.267

Fig. 6.4

Probability of Penetration of Glass
Fragment Missiles Averaged Over
Increments of Missile Mass and
Impact Velocity

Target: Abdomen of Dogs

Fig. 6.5

Expected Missile Penetrations for Given
Log Mass and Log Velocity
Intervals

Target: Abdomen of Dogs

Percent of Total Missile Sample
Expected to Penetrate

Velocity, ft./sec.

Missile Mass, gms.

Expectation of Penetration Expressed as
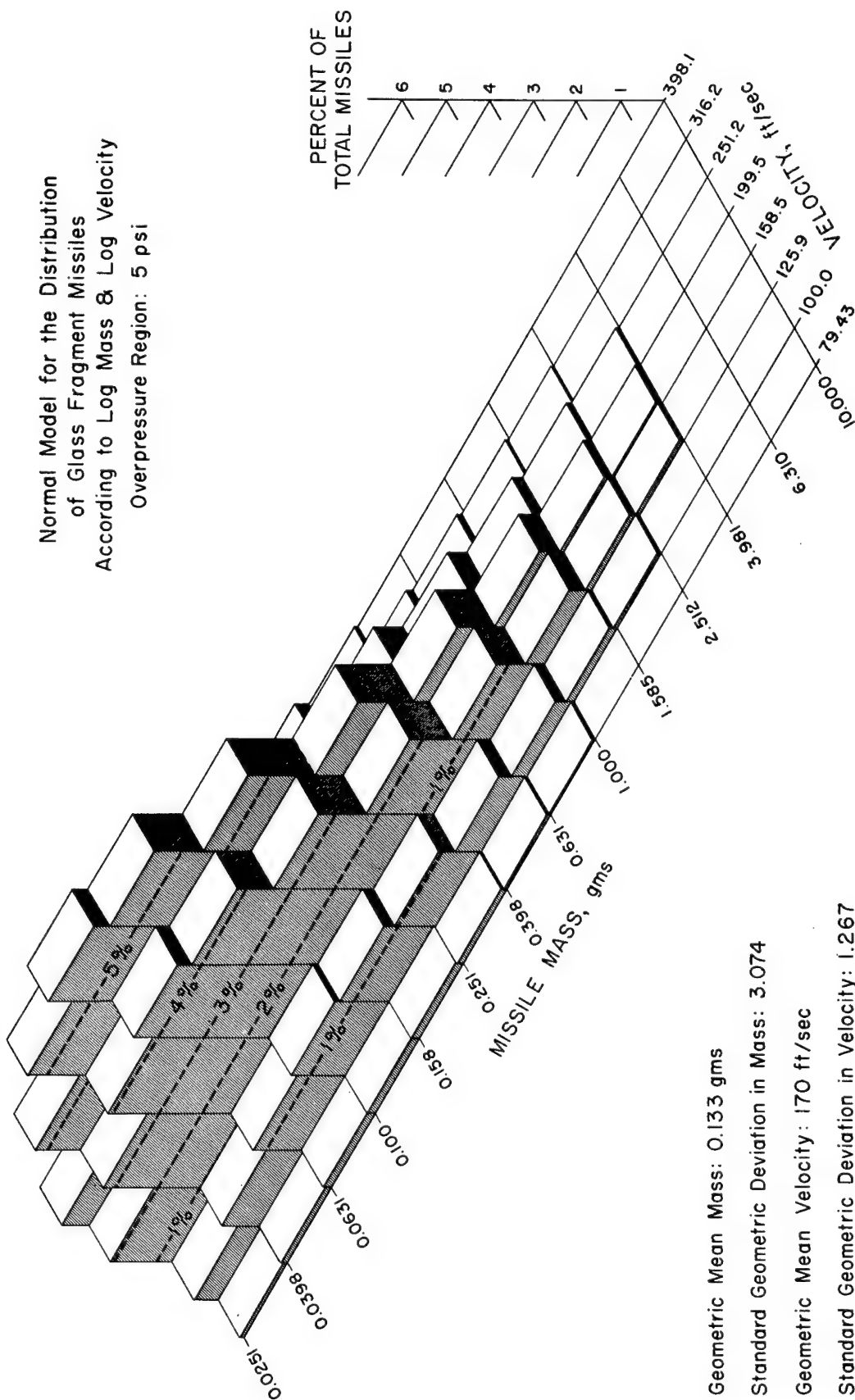Percentages of Total Missile Sample
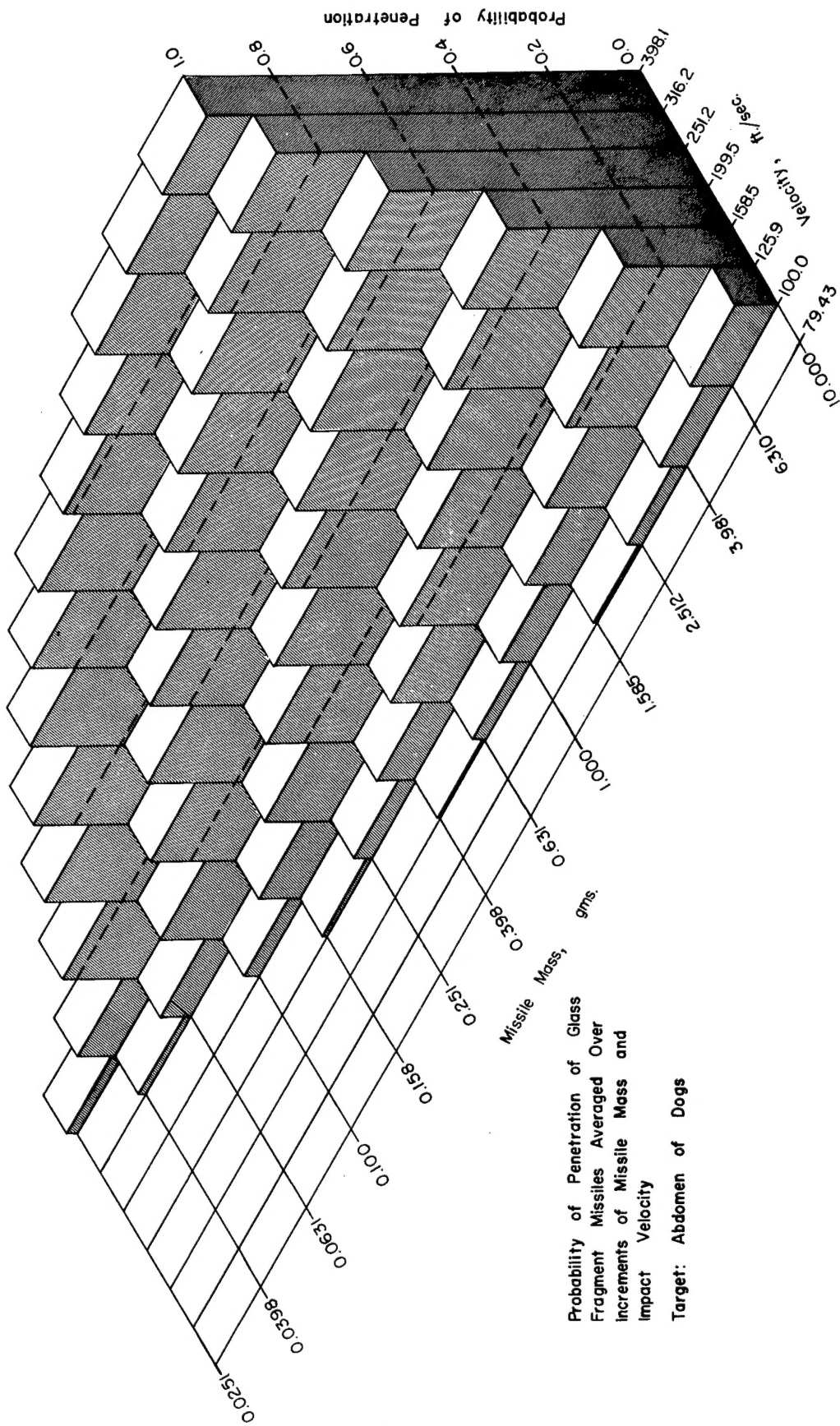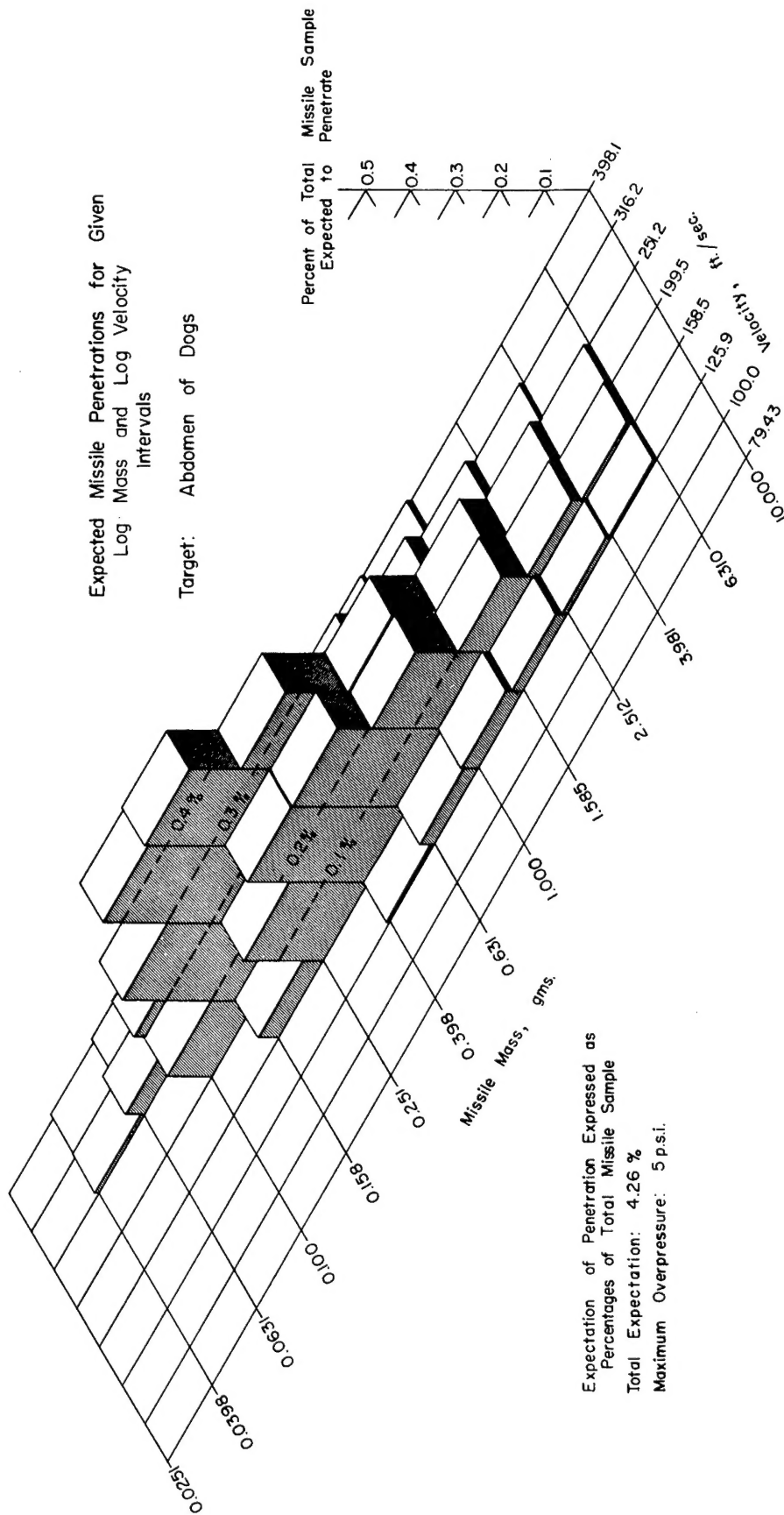Total Expectation: 4.26 %
Maximum Overpressure: 5 p.s.i.

Fig. 6.6

Expected Frequency of Penetration as a Function of Maximum Overpressure

Computed for Glass Missiles Occurring About 10 ft. Behind Windows Facing Blast

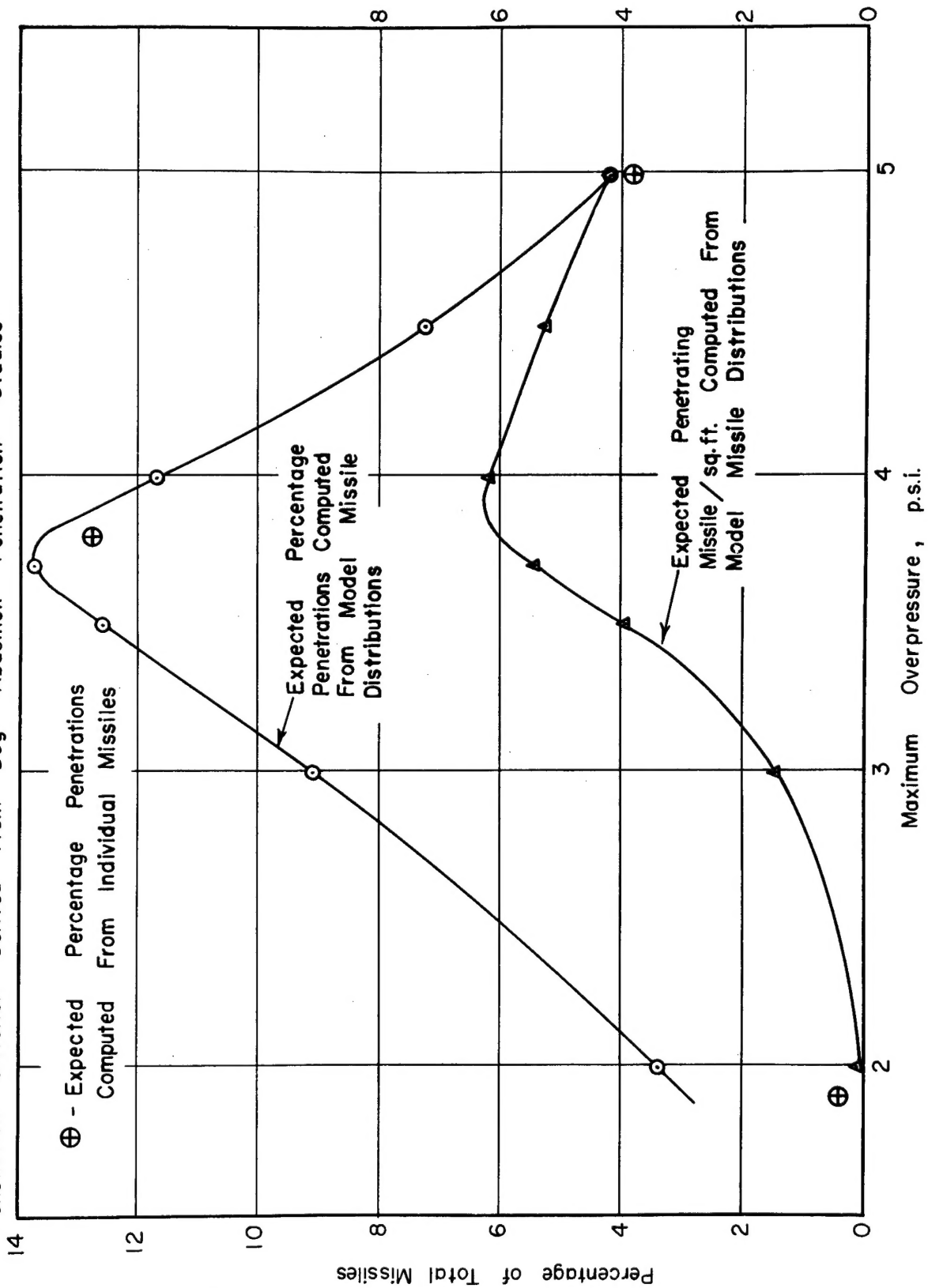Penetration Criterion Derived From Dog Abdomen Penetration Studies

⊕ - Expected Percentage Penetrations Computed From Individual Missiles

Expected Percentage Penetrations Computed From Model Missile Distributions

Expected Penetrating Missile / sq. ft. Computed From Model Missile Distributions

Maximum Overpressure, p.s.i.

Percentage of Total Missiles

Missiles / sq. ft.

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